when combined with ultra-wideband propagation data from a variety of environments (e.g., dense urban and high-rise building interiors), may go a long way toward solving some of the fading problems encountered in mobile communications.

My model of the impulse radio system at this time also supports going to higher pulse repetition rates as a potential method for increasing the capacity of the system. Additional capacity can also be achieved by antenna sectoring and the application of other Pulson proprietary techniques.

I hope that these comments will be of use to you.

Sincerely,

Robert A. Scholtz

R. A. Scholtz

EXHIBIT C

RAINES ENGINEERING

Electromagnetics and Antennas

13420 Cleveland Drive

Potomac, Maryland 20850

(301)279-2972

PROPAGATION OF GAUSSIAN MONOCYCLES INSIDE A SINGLE STORY OFFICE BUILDING

November 9, 1992

Report Prepared for:

Pulson Communications Corporation
8280 Greensboro Drive
Suite 500
McLean, Virginia 22102-3807

CONTENTS

INTRODUCTION

This report describes time-domain measurements of Gaussian monocycle radio waves propagating inside a single-story office building. Also described are a variety of numerical transformations performed on those measurements, including Fourier transforms, auto and cross correlations, and ambiguity functions.

There were at least two reasons for performing the measurements and numerical transforms. First, we wished to determine that some sort of useable waveform could propagate throughout a complicated office environment. By "useable", we mean that information could be successfully transmitted using that waveform. Second, we wished to understand how that waveform might be distorted due to the geometry, contents, and material constants of an office environment.

The above two reasons are closely related. A distorted waveform may still be highly useable, if the receiving process includes coherent integration. We shall elaborate on this in a later section. For now, however, we simply note that we can compensate for distortion by accumulating (i.e., integrating) a sequence of waveforms. In fact, in actual laboratory experiments, music has been successfully transmitted through walls and other obstacles. The price we pay for coherent integration is a decrease in information rate. So, there will be a trade off between distortion and information rate.

Distortion of propagating waveforms follows from two mechanisms, scattering and dispersion. Scattering of electromagnetic waves occurs at discontinuities along the propagation path (e.g., the interface between air and a conducting material, or the boundary between between materials with different dielectric constants.) Such discontinuities include smooth surfaces such as walls, floors, ceilings, and large sections of furniture. They also include corners and edges.

Scattering can distort a monocycle waveform in at least three ways. First, for certain geometries, it results in constructive and destructive wave interference with individual monocycles. Second, it results in complete echoes. These phenomena are collectively called "multipath interference". Third, different frequency components of the monocycle scatter with different amplitudes and time delays (i.e., phase shifts), at least in theory. So, the scattered waveform may not resemble the incident monocycle.

Dispersion results from nonuniform propagation of electromagnetic waves through various barriers, such as dry wall, paneling, cinder block, and insulation. By "nonuniform propagation" is meant that the different frequency components of the Gaussian monocycle exhibit different time delays and attenuations as they pass through these materials. The resultant waveform which emerges from the barrier may be substantially different than the original, incident monocycle.

The different numerical transforms mentioned above help to quantify the effects of scattering and dispersion.

The measurements reported here were not exhaustive; however, they did demonstrate a variety of distortion effects. In particular, we observed numerous echoes and variable attenuation in the time-domain, and wandering notches in the frequency-domain. More systematic measurements and development of a corresponding mathematical model useful for performance predictions are, therefore, advisable.

As we have already mentioned, distortion does not mean the waveform is not useable. It simply means that the Impulse Radio receiver must include a coherent integrator, and that there will be a trade off between distortion and information rate. We shall expand on this process in a later section.

DESCRIPTION OF THE PROPAGATION PATHS

Exhibit 1 shows the office area of interest. The receiver was fixed at a location within the laboratory. The transmitter was moved to four different sites: 1) the laboratory, about 3 meters distant from the receiver; 2) Charles' office; 3) the men's lavatory; and 4) Sue's office. Of these, the first was the best approximation to a line-of-site radio link, though some scattering was observed. The received waveform in this case was the reference against which others were compared. At the remaining sites the transmitter and receiver were separated by multiple interior walls, which were of wood frame and dry wall construction.

Exhibits 2 through 6 show the interior walls blocking the straight line propagation path, starting at Sue's office and ending inside the laboratory. It is seen that large bookshelves are obstacles in addition to the actual walls.

Exhibit 7 shows an alternative propagation path down a corridor passing by Sue's office, the men's lavatory, Charle's office, and into the laboratory.

LABORATORY WAVEFORM

Exhibit 8 shows the received waveform with the transmitter in the laboratory about 3 meters distant from receiver. The idealized waveform is observed within the interval from about 6 to 10 nanoseconds. The waveform is also nonzero for times greater than 10 nanoseconds. This part is probably scattering.

It is not difficult to estimate the origin of the scattering. To that end, note that electromagnetic waves propagate in empty space with a velocity of about one foot per nanosecond. Using that velocity, Exhibit 8 suggests that the propagation path for the scattered wave was about four feet longer than the direct propagation path. Using simple geometry, it appears that scattering occurred at the corner of Larry's office.

Exhibit 9 shows the Fourier transform of the time-domain waveform. The magnitude-squared of this mathematical function is often interpreted physically as the power density of a signal, in units of watts per Hertz. The Fourier transform was computed numerically, using the formula,

$$G(f) = \int_{-\infty}^{\infty} dt\, g(t)\, e^{-j 2\pi f t} \tag{1}$$

It is seen that the maximum signal power density occurs at about 675 MHz. There is a notch near 600 MHz, about -22 dB with respect to the maximum. Signal power density is significant (-15 dB or greater) in the frequency range from 1 MHz through 225 MHz.

Exhibit 10 shows the autocorrelation of the time-domain waveform. The physical interpretation of this mathematical function is simply the output of a correlator, such as that found in a matched receiver. In this particular case, the receiver is matched to the signal shown in Exhibit 8. The autocorrelation function was evaluated numerically, using the formula,

$$A(\tau) = \int_{-\infty}^{\infty} dt\, g(t)\, g^*(t-\tau) \tag{2}$$

It is seen that the autocorrelation is maximum for zero delay. That is, when the received signal is synchronized exactly with the desired, or matched, signal, then the output of the correlator is maximum. So far, so good; however, the maximum is not robust. For example, if the received signal is delayed about a nanosecond, then the output of correlator is almost as great, only about -2.5 dB with respect to the maximum. Further, for signal delays through about 11 nanoseconds, the correlator output can be greater than -10 dB with respect to the maximum. So, a matched receiver would probably exhibit difficulty distinguishing between one Gaussian monocycle and the same waveform delayed up to 11 nanoseconds. This is true for individual pulses. Note, however, for the energy accumulated from hundreds or thousands of pulses, -2.5 dB per pulse could mean a substantial difference.

Exhibit 11 shows the autoambiguity function of the time-domain waveform. This was computed numerically using the formula,

$$\chi(f,\tau) = \int_{-\infty}^{\infty} dt\, g(t)\, g^*(t-\tau)\, e^{+j2\pi f t} \qquad (3)$$

The different colors identify magnitudes of the autoambiguity function which are separated by 10 dB. Blue identifies magnitudes ranging from -10 dB through 0 dB (the maximum). Green identifies magnitudes from -20 dB to -10 dB. Cyan identifies -30 dB to -20 dB. Red identifies -40 dB to -30 dB. Yellow identifies magnitudes less than -40 dB.

DISCUSSION OF THE AMBIGUITY FUNCTION

The ambiguity function, introduced in the previous section, is just one special form of a class of mathematical transforms called "wavelets". Recently, these transforms have attracted increasing amounts of attention from communications engineers, and it is likely they will be applied to Impulse Radio. Accordingly, a more detailed discussion here may prove useful.

The use of the ambiguity function for designing radar signals is well established; however, for communication signals its usefulness is still evolving. Historically, it was derived in a straight forward way for use in radar signal processing. Inspection of eq. 3 above shows that the function is simply the cross correlation of a signal with a time-delayed, frequency-shifted version of itself. In other words, it is the cross correlation of an outgoing radar signal with the return signal from a target. The return signal is delayed due to the round trip propagation time of electromagnetic waves. It is frequency-shifted (i.e., Doppler shifted) because the target, in general, is moving. So, the delay time is proportional to the range to the target, and the frequency shift is proportional to its veclocity. It follows that, if the ambiguity function has a distinct and unique maximum, then the range and velocity of the radar target are uniquely determined. Conversely, if the ambiguity function has numerous maxima, then the range and/or velocity are not uniquely determined. That is, they are ambiguous, hence the name "ambiguity function". So, radar engineers endeavor to design waveforms that produce ambiguity functions with distinct and unique maxima.

The extension of ambiguity functions to communication signals is not straight forward, and so we probably do not fully grasp their physical interpretation at the time of this writing. Nonetheless, we can say this about ambiguity functions as applied to communication signals. First, they are a form of scientific visualization. As such, they are a convenient, and perhaps uniquely revealing, tool for comparing waveforms. Second, they are mathematically elegant, in the sense that they emphasize a certain symmetry between the time and frequency domains.

To appreciate the mathematical symmetry, recall our discussion concerning the autocorrelation function, eq. 2. That equation had an obvious physical interpretation, namely, the output of the matched filter in a correlation-type receiver. This filter is matched in the time-domain. That is, it has a prescribed impulse response. When the output of the filter is maximum, the receiver has detected the desired, or "matched" signal.

There is no a a priori reason for designing a matched filter in the time-domain. It is easy to envision an analog to eq. 2 in frequency-space:

$$\tilde{A}(f) = \int_{-\infty}^{\infty} d\nu \, G(\nu) \, G^{*}(\nu - f) \tag{4}$$

The physical interpretation of eq. 4 is the same as eq. 2. It is the output of a matched filter. This filter is matched in the frequency-domain. That is, it has a prescribed frequency response. When the output is maximum, the receiver has detected the desired signal.

Since matched filters in the time and frequency domains are both realistic possibilities, why be forced to choose only one? It is preferable to implement matched filters simultaneously in both domains to detect the general form of communication signal:

$$g(t) = m(t)\, e^{j 2\pi f_0 t} \tag{5}$$

In eq. 5, m(t) is the modulation envelope, and f_0 is the carrier frequency. For example, for the waveform of interest here, m(t) is a brief (about one cycle in duration) Gaussian, and f_0 is about 600 MHz. So, though it is probably desirable, is it possible to design a matched filter in both spaces simultaneously? The answer is: Yes, if we modify the equations 2 and 4 slightly.

To that end, just as eq. 4 is the frequency-space analog of eq. 2, the analog to the autoambiguity function, eq. 3, is:

$$\tilde{\chi}(f, \tau) = \int_{-\infty}^{\infty} d\nu\, G(\nu)\, G^*(\nu - f)\, e^{j 2\pi \nu \tau} \tag{6}$$

Now comes the mathematical elegance! It can be proven, albeit tediously, that eqs. 3 and 6 are not only analogs, they are equals! That is,

$$\tilde{\chi}(f, \tau) = \chi(f, \tau) \tag{7}$$

This is a remarkable result indeed. It means that we can design waveforms with unique maxima simultaneously in the time and frequency domains.

The above discussion concerning symmetry suggests a tentative, practical interpretation of the ambiguity function. It is simply this. A waveform whose ambiguity function has a unique maximum is uniquely identifiable. It can not be mistaken for any other waveform. Is the waveform any more unique than one with a maximum only in the time-domain (i.e., its autocorrelation function)? At the time of this writing, we admit that we do not know.

Using the above interpretation, let us revisit Exhibit 11. Alas, our waveform does not appear to be optimal. There is no distinct, unique maximum, at least using 10 dB increments.

Exhibit 12 is the same as Exhibit 11, except that the separation between colors corresponds to 6 dB instead of 10 dB. That is, blue identifies magnitudes from -6 dB through 0 dB, and yellow identifies magnitudes less than -30 dB. In general, the same comment applies. There are obviously fewer maxima than in Exhibit 11; however, there is still no unique one.

Exhibit 13 is the same as Exhibit 11, except that the separation between colors corresponds to 3 dB instead of 10 dB. That is, blue identifies magnitudes from -3 dB through 0 dB, and yellow identifies magnitudes less than -15 dB. The situation has improved. There are now only two maxima (i.e., blue regions). We must ask, however, if we can confidently detect the relative magnitude of individual, probably very weak, monocycles to within 3 dB.

Our ambiguity function analysis suggests that individual monocycles are not very optimal, in the sense of being uniquely identifiable. This does not say anything, however, about sequences of many monocycles. The ambiguity function for such sequences, in general, will be very different. It is conceivable that a uniquely identifiable sequence can be designed. This just goes to show what we perhaps long suspected. That is, not much useful information can be transmitted with only one monocycle. We need a sequence, perhaps hundreds or thousands, of them.

CHARLES' OFFICE WAVEFORM

Exhibit 14 shows the received signal in the time-domain when the transmitter was located in Charles' office. There is at least one obvious echo, delayed by about five nanoseconds. Inspection of Exhibit 1 suggests that the echo results from scattering off the exterior wall in Larry's office. There also seems to be some sort of wave interference between the monocycle and its echo.

Exhibit 15 shows the Fourier transform of the time-domain signal. The peak power density appears in the vicinity of 650 MHz. Comparison with Exhibit 9 (the Fourier transform of the Laboratory waveform) suggests that the office walls are functioning as high-pass filters. The low-frequency components (about 1-375 MHz) are much weaker (by about 15 dB) in Exhibit 15 than in Exhibit 9. Also, there seem to be some notches at about 750 MHz, 825 MHz, and 900 MHz. These might be related to the thicknesses and dielectric constants of the walls. Beyond 1200 MHz, the high-frequency components are much stronger than in Exhibit 9. The reason for this is not obvious. It might be a numerical artifact due to the finite amount of data from the time-domain.

Exhibit 16 is the cross correlation of the time-domain waveform with the waveform of Exhibit 8 (the Laboratory waveform). It was computed numerically using the formula,

$$A_{gh}(\tau) = \int_{-\infty}^{\infty} dt\, g(t)\, h^*(t-\tau) \tag{8}$$

The cross correlation function is the output of a correlator which is matched to the Laboratory Waveform (Exhibit 8). That is, the correlator is expecting the Laboratory waveform, but it actually received Exhibit 14. There is clearly no robust maximum, if there is any maximum at all. The correlator will exhibit difficulty distinguishing among waveforms with delays ranging from 1 through about 6 nanoseconds. There is less than 10 dB difference between maxima from delays through 12 nanoseconds.

Exhibit 17 is the cross ambiguity function of Charles' Office Waveform (Exhibit 14) with the Laboratory Waveform. It was computed numerically according to the formula,

$$\chi_{gh}(f,\tau) = \int_{-\infty}^{\infty} dt\, g(t)\, h^*(t-\tau)\, e^{j2\pi f t} \tag{9}$$

This exhibit should be compared with Exhibit 11. The color legends are the same for both exhibits. There are obvious differences in the blue regions, which represent the maxima. There are perceptible differences in the other regions.

Exhibit 18 is the same as Exhibit 17, except that the colors correspond to 6 dB separation in magnitude instead of 10 dB. This exhibit should be compared with Exhibit 12. Again, there are obvious differences in the both the blue and green regions.

Exhibit 19 is the same as Exhibit 17, except that the colors correspond to 3 dB separation in magnitude. This exhibit should be compared with Exhibit 13.

MEN'S LAVATORY WAVEFORM

Exhibit 20 shows the received time-domain signal when the transmitter was located in the men's lavatory. There are clearly multiple echoes. The echo which is delayed by about 6 nanoseconds appears stronger than the initial received signal. Reference to Exhibit 1 provides a plausible explanation. The initial signal propagated through no less than five walls and was attenuated accordingly. The echo was reflected from the far side of the corridor and propagated through only one or two walls.

Exhibit 21 shows the Fourier transform of the time-domain signal. The peak power density appears at about 600 MHz. There are many notches which are probably due to resonances with the particular geometry of the office area, rather than the original waveform. The broad notch (about 150-300 MHz) corresponds to a wave length of 3 to 6 feet. The dimensions of the men's lavatory are close enough to suspect it as a resonant cavity type of reject filter. There is a deep notch (about 35 dB) near 700 MHz. There are numerous notches at frequencies beginning at about 850 MHz.

Exhibit 22 is the cross correlation function of the time-domain waveform with the Laboratory Waveform (Exhibit 8). This represents the output of a correlator which expects the Laboratory Waveform and actually receives the Men's Lavatory Waveform. There is a global maximum at about 3 nanoseconds delay time. It is only about 1 dB or so greater than other, local maxima. So, a receiver would exhibit difficulty distinguishing this waveform from its many echoes.

Exhibits 23 through 25 are the cross ambiguity function of the Men's Lavatory Waveform with the Laboratory Waveform. These should be compared with Exhibits 11 through 13, respectively. About all we can say at the time of this writing is that there are perceptible differences.

SUE'S OFFICE WAVEFORM

Exhibit 26 shows the received signal in the time-domain when the transmitter was located in Sue's Office. An echo with a delay of about 5 nanoseconds is also observed. Both signals are very noisy because they are weak, which indicates they propagated through no less than six walls. The echo probably was reflected from the exterior wall of the Office Supply Storeroom.

Exhibit 27 shows the Fourier transform of the time-domain signal. As in previous cases, numerous notches are observed, each corresponding to a certain room resonance. The maximum power density appears near 500 MHz.

Exhibit 28 shows the cross correlation function of Sue's Office Waveform with the Laboratory Waveform. There is a global maximum, but it is only 1 dB or so different than other, local maxima. So the correlator will exhibit difficulty distinguishing this waveform from its echoes and slightly delayed versions of itself.

Exhibits 29 through 31 shows the cross ambiguity function of Sue's Office Waveform with the Laboratory Waveform. These should be compared with Exhibits 11 through 13, respectively. There are perceptible differences.

COHERENT INTEGRATION

Based upon the experimental observations and numerical computations of the previous sections, Impulse Radio seems well suited to coherent integration. That is, a signal may be successfully received as a sequence of pulses, even though individual pulses have been distorted by scattering, dispersion, and other propagation phenomena. An especially desirable property of coherent integration is that the longer the sequence, the greater the signal-to-noise ratio of the received signal.

The theoretical foundations for reception by coherent integration are described concisely by Minkoff (1992). His discussion is reproduced here in Appendix 2. In the following paragraphs, we summarize his results.

Briefly, Minkoff distinguishes among four different kinds of signal reception: 1) incoherent detection; 2) coherent detection; 3) incoherent integration; and 4) coherent integration.

Let us elaborate on the above first by distinguishing between "detection" and "integration". By "detection", he means the confident reception of a single pulse. By "integration", he means the confident reception of a sequence of pulses. An individual pulse in the sequence could be lost in the noise; however, with a long enough sequence, that loss could be tolerated, with no loss of information. As we have already mentioned, Impulse Radio is well suited to integration.

We continue by distinguishing between "incoherent" and "coherent". By "incoherent", Minkoff means that the receiver uses a bandpass filter to reject some of the noise. The bandwidth of the filter is matched to the bandwidth of a pulse or pulse sequence. Mathematically, however, a complete description of any filter or any signal must include both magnitude (i.e., bandwidth) and phase. For incoherent reception, no effort is made to identify the phase of the signal or to match the filter to that phase. Therefore, some useful signal power is necessarily be wasted. By "coherent", he means that the receiver uses a matched filter to reject noise. As the name implies, such a filter matches the pulse or sequence in both magnitude and phase. In the case of Impulse Radio, the phase of the sequence (i.e., the timing between pulses) is well known a priori. Therefore, Impulse Radio is well suited to coherent integration, as already mentioned.

Coherent integration is especially attractive for Impulse Radio, for at least one more reason. Successful coherent integration does not require phase matching to individual pulses. That is, the individual pulses can be distorted (e.g., due to propagation effects), and coherent integration still works! It is only the timing between pulses that matters. If the individual pulses are not distorted, then we can squeeze an extra 3 dB of signal-to-noise ratio out of the receiver; however, this is small change compared to the total we can achieve.

The advantages of coherent over incoherent, and of integration over simple detection, can be expressed quantitatively with simple formulas. If the signal-to-noise ratio obtained using incoherent detection is SNR_0, then the SNR obtained using coherent detection is:

$$SNR = 2 \cdot SNR_0 \tag{10}$$

The SNR obtained using incoherent integration of M pulses is:

$$SNR = \sqrt{M} \cdot SNR_0 \tag{11}$$

The SNR obtained using coherent integration is:

$$SNR = M \cdot SNR_o \tag{12}$$

The SNR obtained using coherent integration with matched filtering of individual pulses includes an additional 3 dB:

$$SNR = 2M \cdot SNR_o \tag{13}$$

From eqs. 11 through 13, we see that an arbitrary SNR is achievable by integrating over enough pulses. The disadvantage is a decrease in information rate. That is, we need to integrate over M pulses to receive one bit of information. In an ideal, noise free environment, M pulses could be used to transmit M bits of information.

CONCLUSIONS

We have measured time-domain signals received from transmitters in four different locations: 1) the laboratory; 2) Charles' office; 3) the men's lavatory; and 3) Sue's office. Of these, only the first (the Laboratory Waveform) included an uninterrupted straight line propagation path. The others required propagation through walls and reflections from walls.

We analyzed the signals in four different ways: 1) in the time-domain; 2) in the frequency-domain, using a numerical Fourier transform; 3) numerically cross-correlated with the Laboratory

Waveform; and 4) as a cross ambiguity function with the Laboratory Waveform.

The purpose of the measurements and subsequent numerical transformations was twofold. First, we wished to determine that some sort of useable waveform could propagate within a complicated office environment. Second, we wished to investigate how that waveform was distorted by the various obstacles in that environment. These purposes are closely related. We emphasize that a distorted waveform is still highly useable, if the receiver includes a coherent integrator. Integration compensates for distortion by accumulating sufficient signal energy from a sequence of waveforms rather than from an individual waveform. Moreover, the more waveforms that are integrated, the more useable energy is accumulated, until an arbitrarily high signal-to-noise ratio is obtained. In fact, during actual laboratory experiments, music was successfully transmitted within the office environment. The price we pay for coherent integration is a decrease in information rate. That is, using integration, M pulses are required to transmit one bit of information. In contrast, under ideal, noiseless conditions, the same M pulses could be used to transmit M bits of information.

In the time-domain, all signals exhibited multi-path, or echoes. Most of the echoes were understandable in terms of reflections from various walls. In at least one case, the echo was stronger than the initial received signal because it passed through fewer walls.

In the frequency-domain, numerous notches were observed, at precise frequencies which varied from signal to signal. These almost certainly are due to assorted room resonances, rather than being intrinsic to the radiated waveform. Similarly, the peak power density wandered between 500 MHz and 700 MHz. In open space, the peak power density is probably at a fixed frequency. Indoors, however, the room resonances attenuate that peak variably.

The cross correlation functions show that individual monocycles are not robustly detectable. That is, a correlator will exhibit difficulty distinguishing among one monocycle and echoes delayed variously between 1 and about 12 nanoseconds. In most cases, there is a slight global maximum in the cross correlation function; however, it is only 1 dB or so greater than numerous other local maxima. In the presence of any significant noise, a 1 dB difference is not sufficient to confidently detect the precise arrival time of an individual monocycle at the receiver. This confirms our contention that the Impulse Radio receiver must be designed around coherent integration (i.e., accumulation of signal energy from a sequence of waveforms) rather than coherent detection (i.e., extraction of sufficient energy from an individual waveform).

The cross ambiguity function is a special form of a class of mathematical transforms called "wavelets". Recently, these have attracted increasing amounts of attention from communication engineers. In this report, we have used the cross ambiguity function chiefly as a type of scientific visualization. For quantitative analysis, we continue to rely upon the cross correlation function, described in the above paragraph.

This report has described measurable effects due to office geometry and material constants. Multi-path or echoes in the time-domain and notches in the frequency-domain are the most obvious examples. Now that these effects have been shown to exist, a future investigation should systematically isolate and corroborate them with models from classic electromagnetic theory. Together with the theory of coherent integration for radio receivers, we should be able to predict information rate for various office parameters.

ACKNOWLEDGMENTS

The author thanks Mr. Ed Osborne for performing the measurements at Time Domain Systems, Inc., Huntsville, Alabama. Mr. Charles Carter of Time Domain Systems provided helpful discussions concerning coherent integration.

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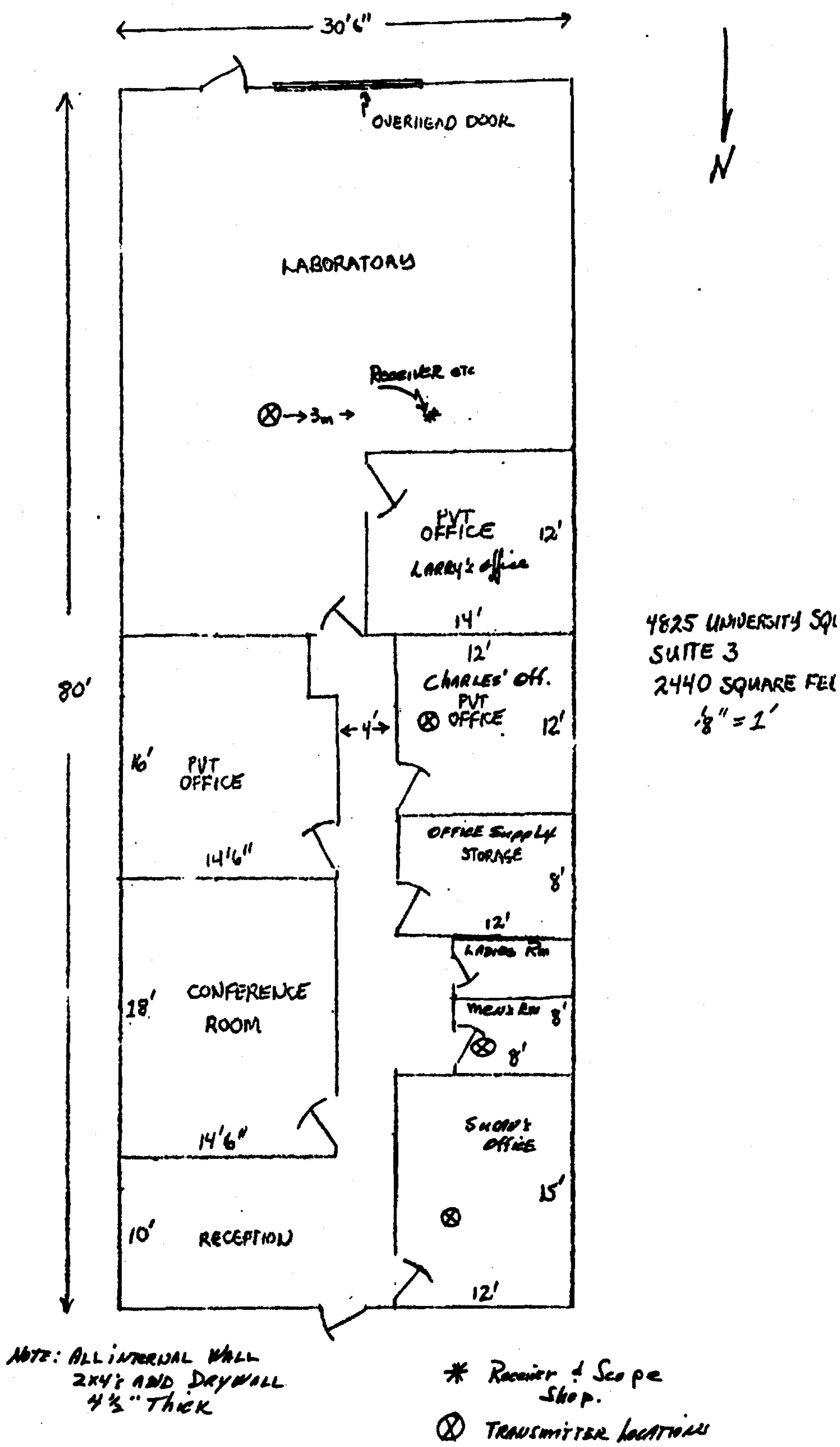
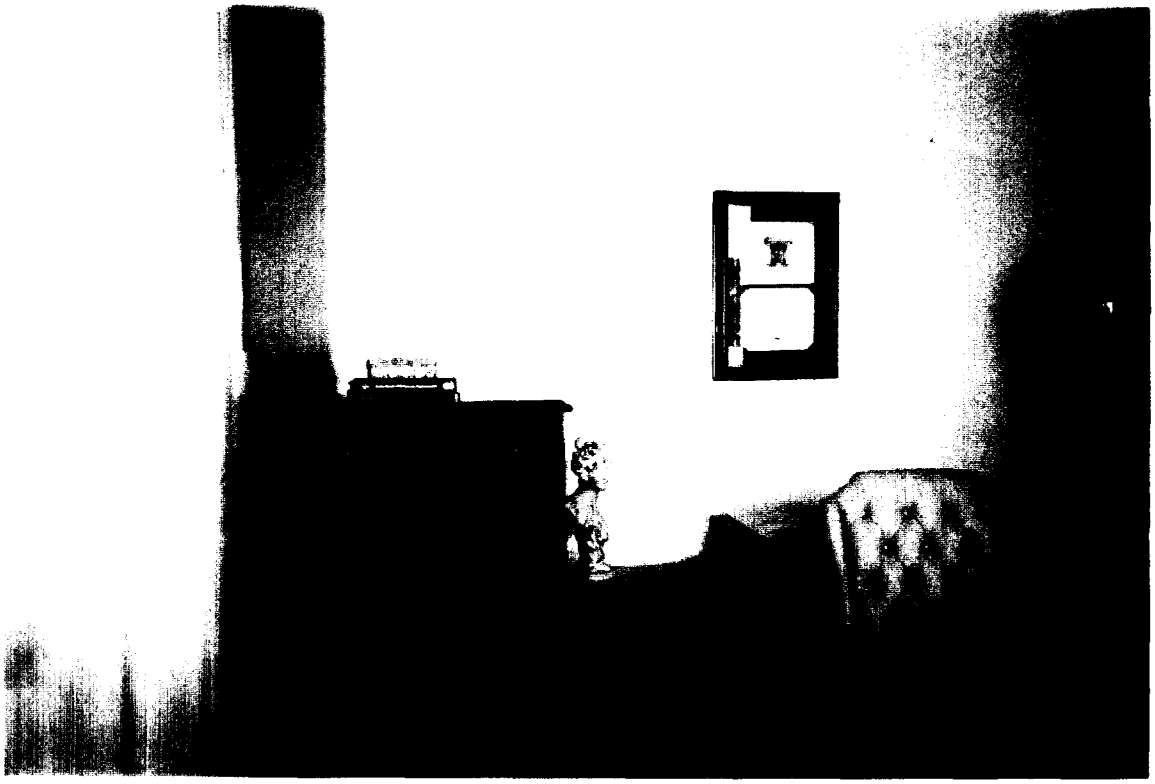


Exhibit 1. Floor plan of office enivironment used for measurements.



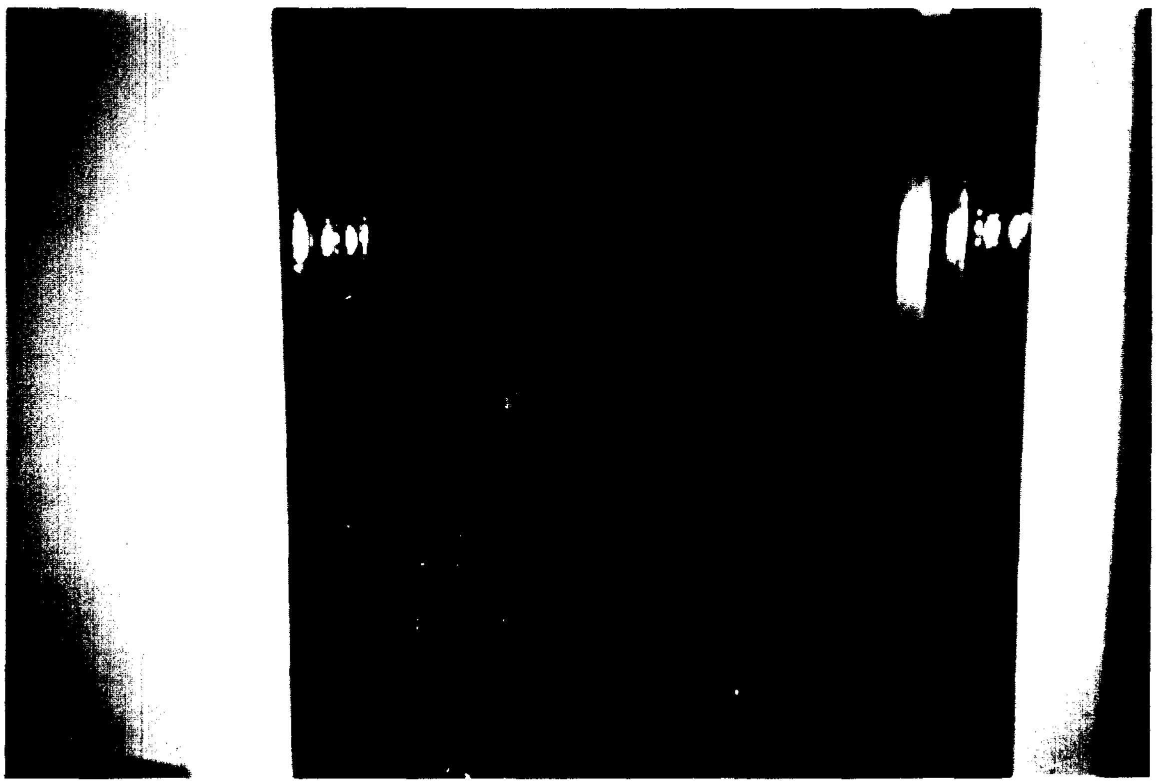


Exhibit 2. Obstacles along the straight line propagation path: interior wall of Sue's office (above); men's lavatory (below).